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PROBLEM OF THE EFFECT OF CAPTURE CENTERS ON THE PHOTOCONDUCTIVITY OF SEMICONDUCTORS AT HIGH ILLUMINATION LEVELS

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Discussion of the calculation of photoconductivity in homogeneous semiconductors for certain cases in which the solution of the appropriate second-order nonlinear differential equations with indivisible variables can be obtained in elementary functions.

An investigation of excess photoconductivity is one effective method of /40* studying nonequilibrium electron processes taking place in semiconductors.

The phenomenon of photoconductivity at low photoproduction levels of electron-hole pairs has been extensively studied in the literature. There is a comparatively small number of works devoted to photoconductivity in the case of large light fluxes. This is due to the fact that the problem of a theoretical investigation of photoconductivity is a nonlinear problem in the general case for large illuminations.

This work presents the results derived from computing photoconductivity in homogeneous semiconductors for certain cases, in which the solution of the corresponding nonlinear differential equation of the second order, with nonseparable variables, may be obtained in terms of elementary functions.

Under nonequilibrium conditions, the behavior of electrons and holes in the semiconductor may be described by the following system of equations

$$\frac{\partial p}{\partial t} = G - R - \frac{1}{q}\operatorname{div}\vec{j}_p, \tag{1}$$

$$\vec{j}_p = q\mu_p p\vec{E} - qD_p \operatorname{grad} p, \tag{2}$$

$$\vec{j}_n = q\mu_n n\vec{E} + qD_n \operatorname{grad} n, \tag{3}$$

$$\operatorname{div}\vec{E} = \frac{4\pi\rho}{\varepsilon} \tag{4}$$

(G -- generating function, R -- recombination rate. The remaining notation is that which is customarily employed).

In the one-dimensional case, let monochromatic light fall normal to the semiconductor surface (x = 0), so that

$$G = \beta k I_0 \exp(-kx),$$

so that β is the quantum yield, k -- light absorption coefficient, I_0 -- light intensity on the illuminated surface. In addition, in the forbidden zone of the semiconductor (n-type) let us assume that there are capture levels (of the

* Numbers in the margin indicate pagination in the original foreign text.

β-type) for holes whose concentration N_n slightly exceeds the donor concentration N_d -- in addition to recombination centers insuring a small lifetime τ. The density of the volume charge is then $\rho = q(p + N_d + N_+ - n)$. Here $N_+ = pN_n/(p_1 + p)$ is the hole concentration at the capture levels. /41

Assuming that $\vec{j} = \vec{j}_p + \vec{j}_n = 0$, we have the following from equations (2) - (3) under the condition of quasineutrality ($n \simeq p + N_d + N_+$):

$$j_p = -qD \cdot \frac{\partial p}{\partial x}, \tag{5}$$

where

$$D = bD_p \frac{2p + N_d + \frac{2p_1 + p}{(p_1 + p)^2} pN_n}{(b+1)p + b\left(N_d + \frac{pN_n}{p_1 + p}\right)} \tag{6}$$

is the coefficient of bipolar diffusion (b -- ratio between electron and hole mobilities). It may be seen from studying expression (6) that $D_p \lesssim D \lesssim 2D_p$. The maximum value of $D \simeq 2D_p$ is obtained if we assume that the capture levels are only slightly occupied ($p \ll p_1$) and have a large concentration ($N_n \gg N_d, p_1$). Therefore, it may be assumed that D is approximately constant, not depending on the concentration of nonequilibrium carriers. Calculations show that such an approximation is satisfied for small ($p \ll N_d$) and high illumination levels ($p \gg N_d$).

The expression for R may be written in the following form

$$R = A_1(np - n_0p_0) + A_2(np_t - n_0p_{t0}) + \eta_n n^2 p + \eta_p p^2 n + \dots \tag{7}$$

Here A_1 and A_2 are the coefficients of quadratic and linear recombination, η_n and η_p -- coefficients of impact recombinations with transfer of energy to an electron and a hole, respectively.

We may find the hole concentration in the traps p_t by employing the principle of detailed balance -- i.e.,

$$A_2(np_t - n_0p_{t0}) = A_3(pn_t - p_0n_{t0}), \tag{8}$$

where A_3 is the coefficient of hole capture by the trap, $n_t = N_t - p_t$ -- electron concentration in the traps, n_0, p_0, n_{t0} and p_{t0} -- equilibrium concentrations of electrons in holes, respectively, in the zones and in the traps. If the hole concentration N_t is small, for large illumination levels ($n' = p' \gg p_t, n_0, p_0$), we obtain the following from equation (8)

$$p_t = \frac{A_3}{A_2 + A_3} N_t. \tag{9}$$

With allowance for (7) and (9), in the stationary state $\left(\frac{\partial t}{\partial t} = 0\right)$, equation (1) assumes the following form

$$\frac{d^2p}{dx^2} = \frac{\gamma_n + \eta_p}{D} p^3 + \frac{A_1}{D} p^2 + \frac{A_2 A_3 N_t}{D(A_2 + A_3)} p - \frac{\beta k I_0}{D} e^{-kx}. \tag{10}$$

This is a nonlinear differential equation of the second order with nonseparable variables. In the general case, it cannot be solved. The solution of this equation may be reduced to determining the quadratures for only the strong (kx >> 1) and faint (kx << 1) light absorption, when the last term in (10) equals zero or is constant. Integrating equation (10), we obtain /42

$$-x = \int_{p(0)}^{p(x)} \frac{dp}{\sqrt{ap^4 + \tilde{b}p^3 + cp^2 + dp + C_1}}, \tag{11}$$

where

$$a = \frac{\gamma_n + \eta_p}{2D}, \quad \tilde{b} = \frac{2A_1}{3D}, \quad c = \frac{A_2 A_3 N_t}{D(A_2 + A_3)}$$

$$d = \begin{cases} 0 \text{ for } kx \gg 1 \\ -\frac{2\beta k I_0}{D} \text{ for } kx \ll 1 \end{cases}, \tag{12}$$

where p(0) and C_1 are the integration constants which may be found from the boundary conditions on illuminated (x = 0) and unilluminated (x = l) surfaces. In the case of strong absorption, they may be written as follows

$$j_p(0) = q\beta kI - qs_1 p(0) = -qD\left(\frac{dp}{dx}\right)_{x=0}, \tag{13}$$

$$j_p(l) = qs_2 p(l) = -qD\left(\frac{dp}{dx}\right)_{x=l} \tag{14}$$

(where s_1 and s_2 are the rates of surface recombination on the leading and trailing surfaces).

For weak light absorption, the boundary conditions may also be described by equations (15) - (16). However, we must set I = 0 in (13) [since photoproduction is taken into account in the equation of continuity (10)].

In the general case, expression (11) is an elliptic integral which is pseudoelliptic under certain conditions -- i.e., it may be expressed in terms of elementary functions. This occurs in the case of surface photoproduction (d = 0), if the collision recombination is negligibly small (a = 0) and the sample thickness is several diffusion lengths of the nonequilibrium charge carriers, so that we have the following on the trailing surface

$$(x = l)\ \frac{dp}{dx} \simeq 0 \text{ and } p \simeq 0, \text{ i.e., } C_1 = 0.$$

Three cases are thus possible: (1) "pure" bimolecular recombination when the influence of the traps and the capture levels is disregarded (c = 0, n = p) [for an eigen semiconductor ($n_0 = p_0 = n_i$) was investigated by T. Moss (Ref. 1)]; (2) bimolecular recombination for a comparatively small concentration of recombination centers, but without allowance for the influence of the capture

levels $\left(n = p,\ c = \frac{A_2 A_3 N_t}{D(A_2 + A_3)}\right)$; (3) bimolecular recombination for a high concentrationof capture levels of the β-type, but without allowance for the influence of traps as recombination centers ($n \neq p$).

In the first case $A_1 = 1/(n_0 + p_0)\tau$ and, according to (11), for the hole distribution we have

$$p = p(0)\left[1 + \sqrt{\frac{p(0)}{6(n_0 + p_0)}} \cdot \frac{x}{L}\right]^{-2}, \tag{15}$$

In accordance with (13), p(0) satisfies the equation

$$p(0)\left[\alpha + \sqrt{\frac{2p(0)}{3(n_0 + p_0)}}\right] = \frac{\beta k I \tau}{L} \quad \left(\alpha = \frac{sL}{D}\right), \tag{16}$$

i.e., generally speaking, the hole concentration on the surface depends non- /43
linearly on the light intensity. The dependence of p(0) on I approaches a linear dependence for rather large α and not very large p(0). If α is small, then $p(0) \sim I^{2/3}$.

The photoconductivity is proportional to the following value

$$P = \int_0^l \frac{p + bn}{b + 1}\, dx = \sqrt{6(n_0 + p_0)p(0)} \cdot L. \tag{17}$$

Calculations have shown that the condition $p(0) \gg p(l)$, under which the distribution of (15) may be found, is satisfied if $\frac{l}{L} \gtrsim 2.45$.

Combining (17) and (16), we obtain

$$\frac{P^2}{6(n_0 + p_0)L}\left[\alpha + \frac{P}{3(n_0 + p_0)L}\right] = \beta k I \tau, \tag{18}$$

i.e., the photoconductivity is cubic ($P \sim I^{1/3}$) or square ($P \sim I^{1/2}$) depending on the relationship between the rate of surface recombination and a certain value which is proportional to the photoconductivity.

In the second case $\sqrt{c} = \frac{1}{L}$ and, according to (11), the hole distribution may be described by the following formula

$$p(x) = \frac{6}{A_1 \tau} B e^{-\frac{x}{L}}\left(B - e^{-\frac{x}{L}}\right)^{-2}, \tag{19}$$

where

$$B = p(0)\left(\sqrt{p(0) + \frac{3}{2A_1\tau}} - \sqrt{\frac{3}{2A_1\tau}}\right)^{-2} \tag{20}$$

is a constant satisfying the relationship

$$\frac{6BD}{A_1 L}\left[B + 1 + \alpha(B - 1)\right](B - 1)^{-3} = \beta k I \tau. \tag{21}$$

We have the following from equations (17), (19) - (21):

$$P\left(1+\frac{A_1\tau}{6L}P\right)\left(1+\alpha+\frac{A_1\tau}{3L}P\right)=\beta kI\tau, \tag{22}$$

It may be seen from this equation that the photoconductivity increases with light intensity linearly at first, then quadratically in a small region of intensity values (in the case $\alpha \gg 1$), and finally cubically for very large intensities $\left[P \gg \frac{6L}{A_1\tau}(1+\alpha)\right]$.

When the influence of the capture levels is investigated, we may calculate the photoconductivity in the two limiting cases of weak ($p \ll p_1$) and strong ($p \gg p_1$) occupation of the levels. We again arrive at the relationships (19) (21), in which $A_1\tau$ must be replaced by $\lambda/(\lambda p_0 + n_0)$ in the case $p \ll p_1\left(\lambda = 1+\frac{N_n}{p_1}\right)$ and by $(n_0 + p_0 + N_n)^{-1}$ in the case $p \gg p_1$.

(a) a) $p \ll p_1,\ n \simeq \lambda p,\ \tilde{b}=\frac{2A_1\lambda}{3D},\quad c=\frac{A_1(\lambda p_0+n_0)}{D}.$

We obtain the following from equations (17) and (21): /44

$$\frac{(b+1)P}{b\lambda+1}\left[1+\frac{(b+1)\lambda P}{6(\lambda p_0+n_0)(b\lambda+1)L}\times\right.$$
$$\left.\times\left[1+\alpha+\frac{(b+1)\lambda P}{3(\lambda p_0+n_0)(b\lambda+1)L}\right]=\beta kI\tau,\right. \tag{23}$$

i.e., the photoconductivity is again linear, square, or cubic, depending on the region of light intensity values. Equation (23) differs from (22) only in the fact that (23) contains the dependence on the concentration of capture centers, which is approximately linear in the case $\lambda \gg 1$.

(b) $p \gg p_1,\ n \simeq p + N_n,\ \tilde{b}=\frac{2A_1}{3D},\quad c=\frac{(n_0+p_0+N_n)A_1}{D}.$

It follows from (17) and (19) that

$$P \simeq \frac{6(n_0+p_0+N_n)L}{B-1}+\frac{b}{b+1}N_n l, \tag{24}$$

from which we have the following, by employing (21):

$$\left(P-\frac{b}{b+1}N_n l\right)\left(1+\frac{P}{bN_n l}-\frac{b}{b+1}\cdot\frac{l}{6L}\right)\times$$
$$\times\left(1+\alpha+\frac{P}{3N_n l}-\frac{b}{b+1}\cdot\frac{l}{3L}\right)=\beta kI\tau. \tag{25}$$

It may be seen from equations (24) and (25) that $P \gtrsim \frac{b}{b+1}N_n l$ always holds when the capture levels are greatly occupied under conditions of high illumination levels. Therefore, the condition $P < 6N_nL$ cannot even be realized for large concentrations of capture centers (naturally, if $l > L$). For large light intensities ($P \gg 6N_nL\,[1+\alpha]$), we obtain the following from (25)

$$P \simeq \frac{b}{b+1} N_n l + \left[18 \beta k I \tau (N_n L)^2 \right]^{1/3}, \quad (26)$$

i.e., the photoconductivity contains two components. One of these components is constant and does not depend on light intensity, and the other component is related to it by a cubic dependence and increases with the concentration N_n as $N_n^2/3$.

Thus, if certain unusual features are not taken into account, the lux ampere characteristic of a thick semiconductor is similar to that which was obtained in the study by T. Moss (Ref. 1). However, the linear dependence of photoconductivity on illumination does not follow from the calculations of T. Moss for high illumination levels, nor for any light intensities. This linear dependence is frequently observed in experiments, and may be obtained if the influence of capture levels is taken into account -- or if the recombination with participation of traps is taken into account along with the bimolecular recombination.

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